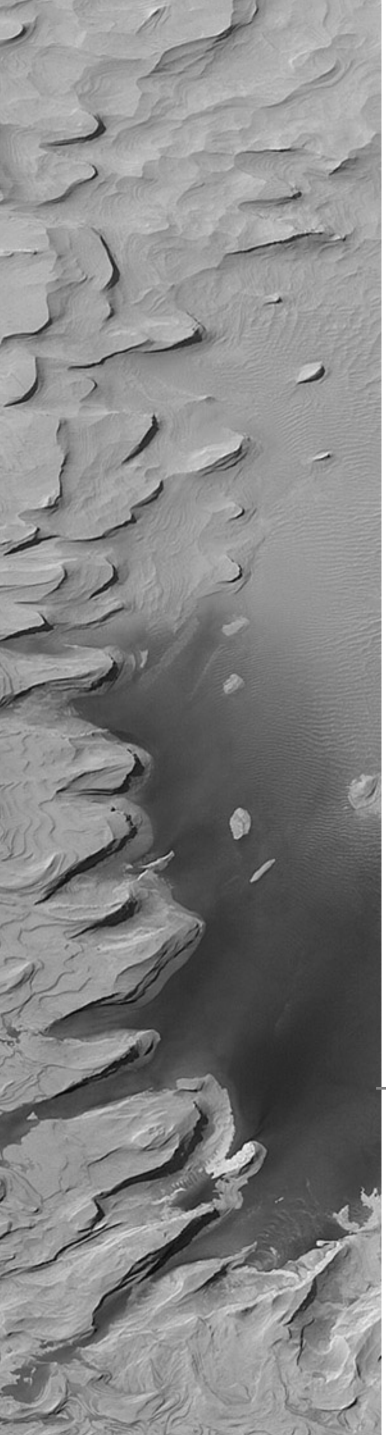

ICAR’05 Workshop on Navigation and Manipulation for Mars Rovers

Stereo Vision Overview

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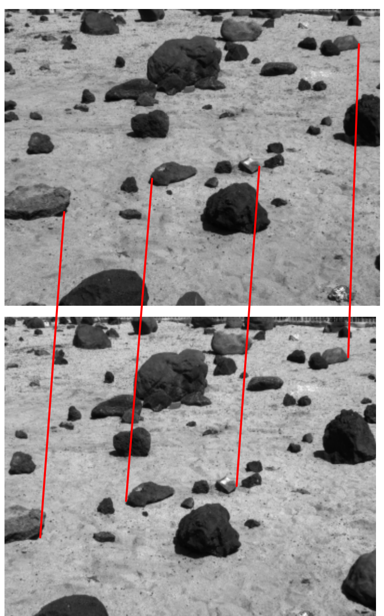
General Overview

- What is stereo vision?
  - 2 or more cameras in known rigid configuration
  - Match pixels in left and right frames
  - Reconstruction of 3D data from 2D information using known camera geometry

Left

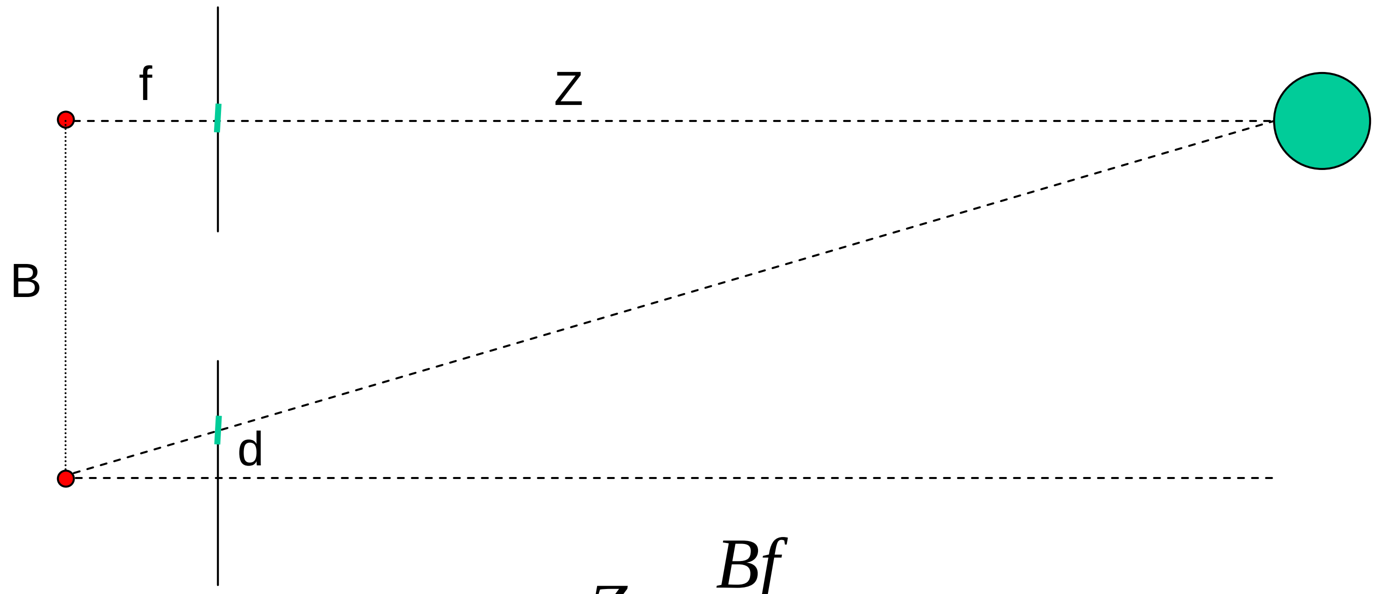
Right



General Overview

- Applications for range from stereo
  - Engineering
    - Navigation and path planning
    - Obstacle avoidance
    - Instrument placement
  - Science
    - Visualization
    - Size and rock density measurements
    - Structure recovery

1-D Sketch of Stereo Triangulation

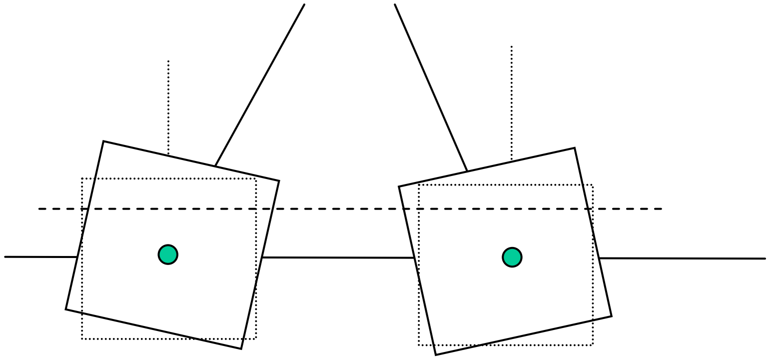


$$Z = \frac{Bf}{d}$$

Must solve correspondence problem.

Stereo in 2-D

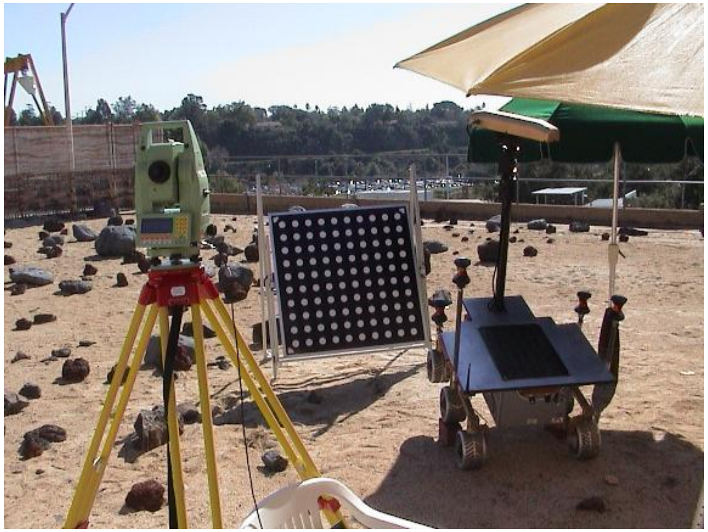
- Straightforward extension from 1-D geometry to 2-D
- However:
  - Solving correspondence problem in 2-D is expensive
  - Camera alignment and image rectification
    - Turns 2-D search into 1-D search



Geometery recovered throught Camera calibration

Camera Calibration

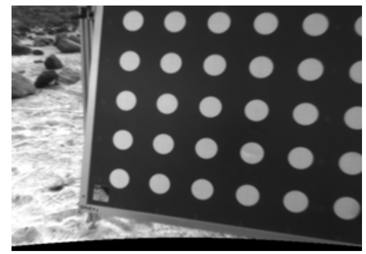
- Extract camera projection geometry in global coordinate frame
  - Parameter estimation from 3-D to 2-D point correspondences
  - Recovered information
    - 6 DoF camera pose
    - 5 linear camera parameters
    - non-linear parameters (number depends on model)
    - CAHVOR(E) model used for Mars Rovers



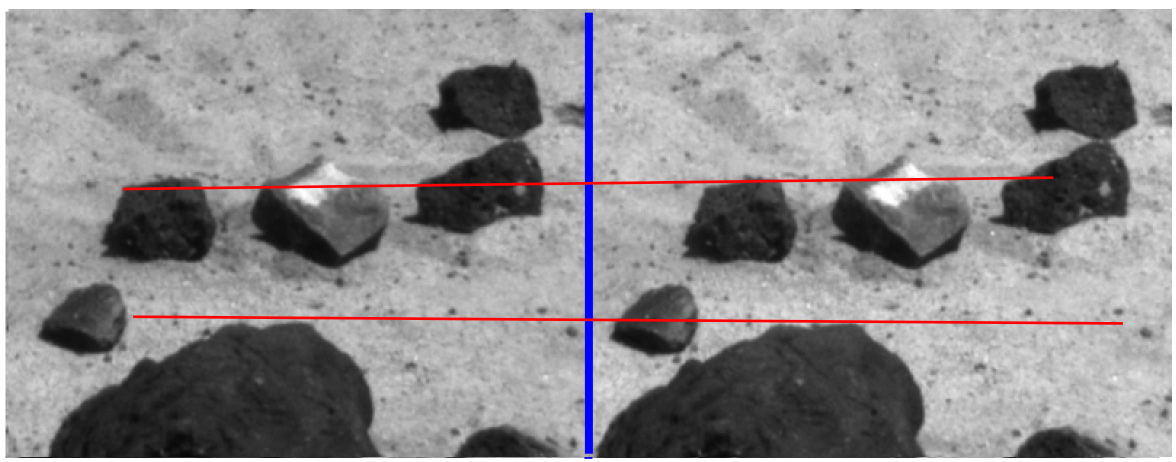
Alternative: Solve simultaneously for 3-D structure of points

Image rectification

- Project data from real imagery to aligned virtual cameras.
  - Remove image non-linearity



- Modify intrinsics (focal length, image center) and camera pointing



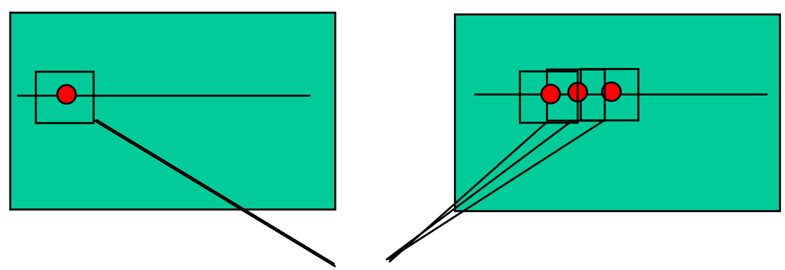
Raw imagery

Rectified imagery

Point correspondence: Correlation

- *Points are matched along individual scanlines*
  - *For each pixel in left image*
    - *Construct box Bl centered at pixel (typically 7 x 7)*
    - *For each pixel in search range in right image*
      - *Construct box Br_d centered at pixel*
      - *Compute sum of absolute difference (SAD) of pixels in Bl and Br_d*
    - *Disparity corresponds to lowest SAD score -> highest similarity between neighborhood of left and right pixel*

***d* = 2**

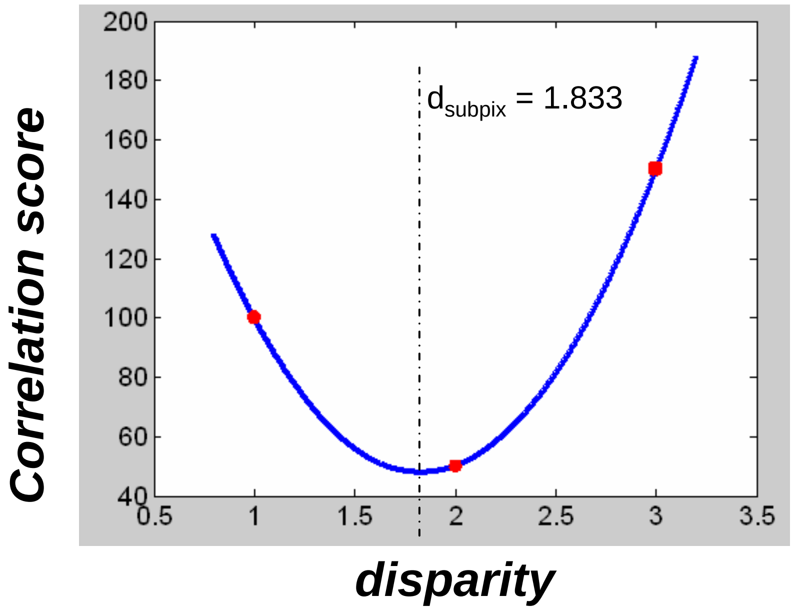


***SAD* = 100**

***Best disparity* = 2**

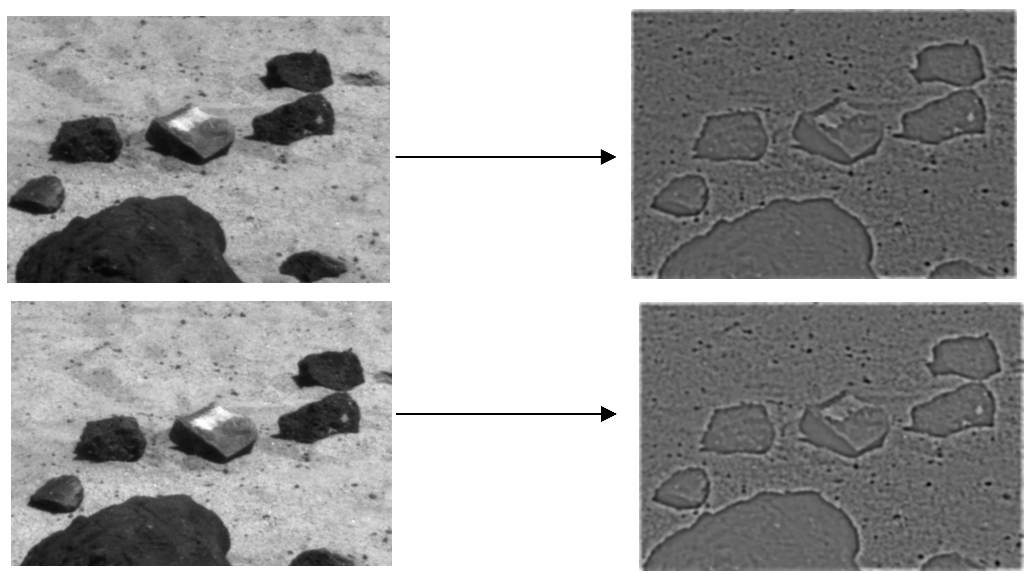
Subpixel refinement

- ***Quadratic interpolation on correlation scores used to find subpixel disaprity***
- ***In preceding toy example SAD(d = 1) = 100, SAD(d = 2) = 50, SAD(d = 3) = 150***
- ***Minimum of best fit parabola at d = 1.833***



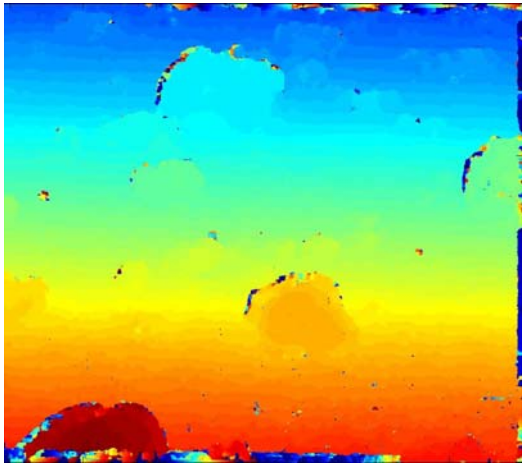
Additional filtering

- *Preprocessing*
  - *Bandpass filter via difference of Gaussians*
    - *Balance photometric differences between cameras*
    - *Remove noise*
    - *Preserve texture*

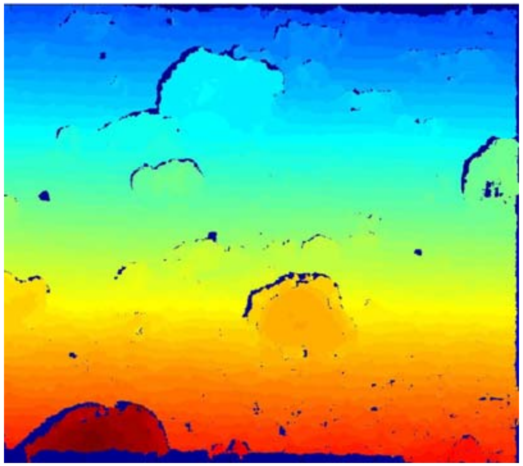


Additional filtering

- *Post-processing*
  - *Blob filtering*
    - *Removes noise from range data*
  - *Left – right line of sight check*

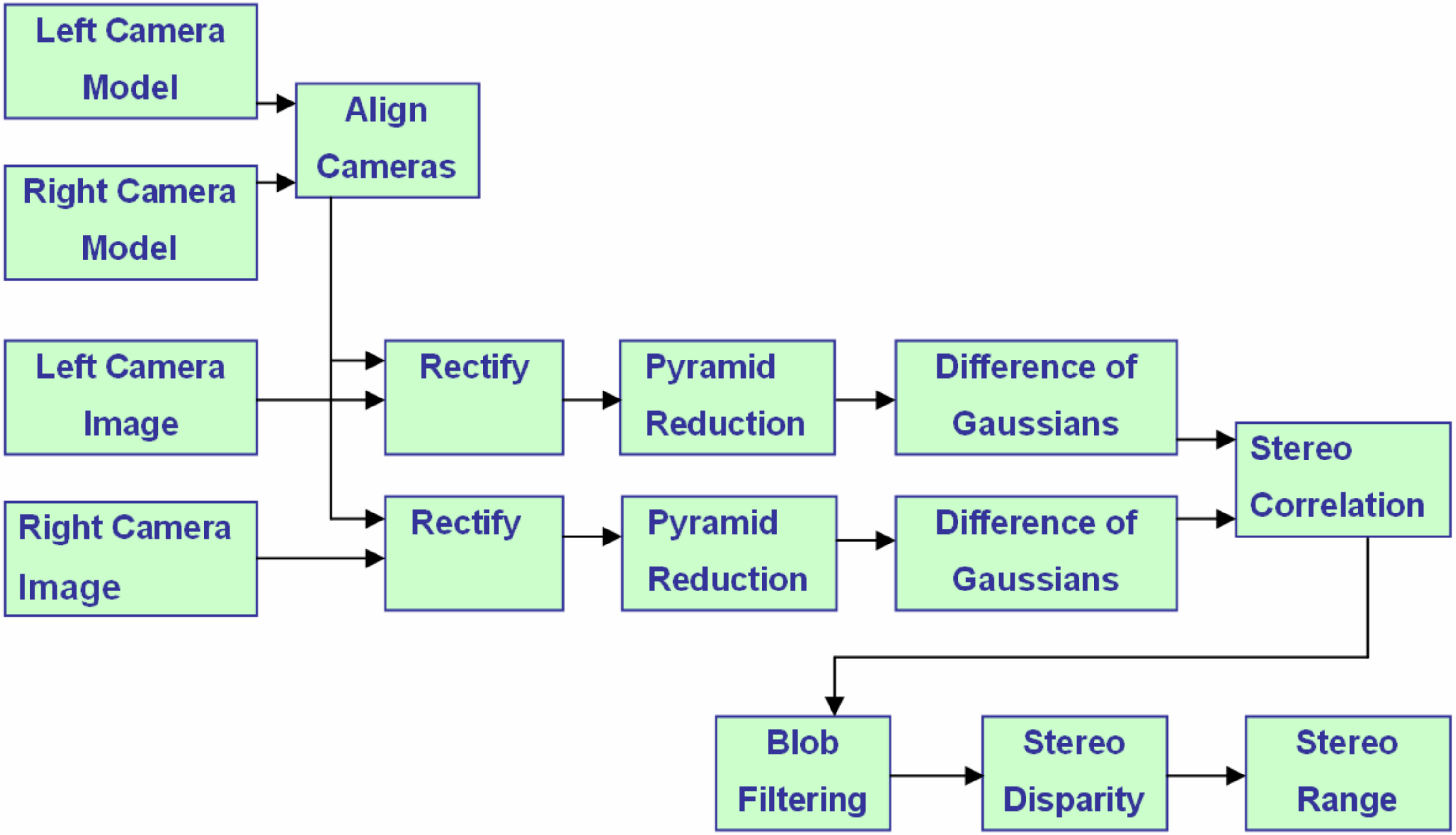


Unfiltered



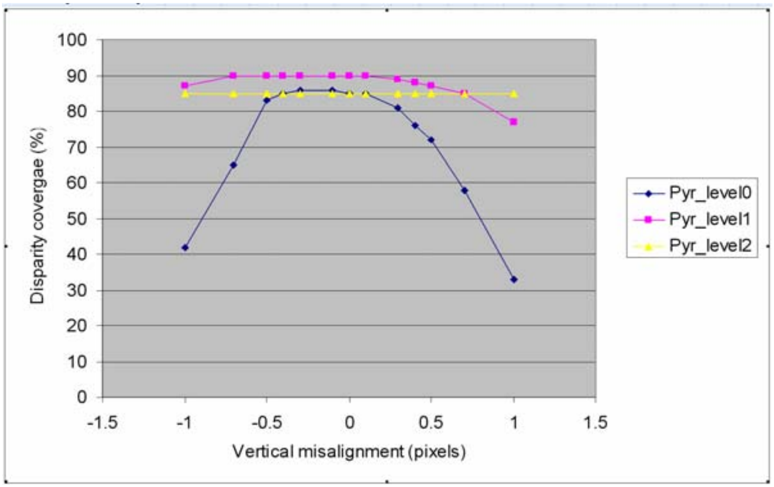
Filtered

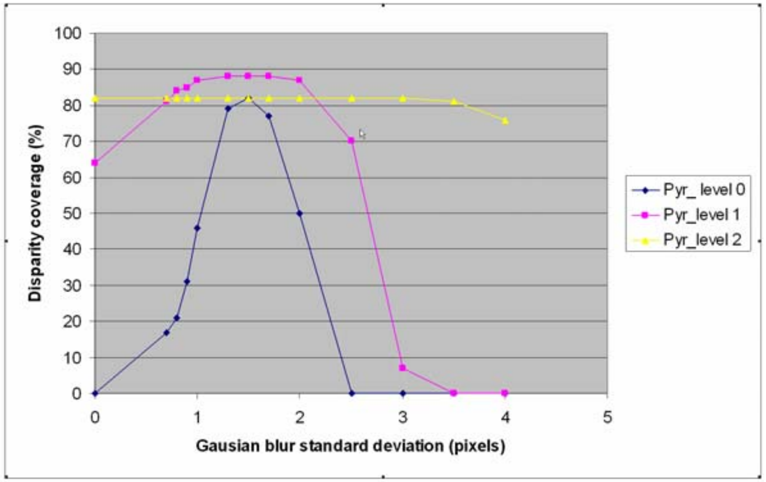
Stereo functional diagram



Error sources

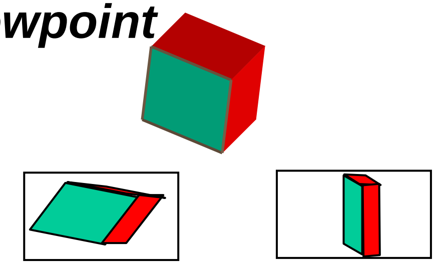
- ***Vertical misalignment***
  - ***Calibration errors***
  - ***Dependence on correlation window size***
  - ***Dependence on Pyramid level***
- ***Poor focus***
  - ***Correlation depends on spatial frequency content***

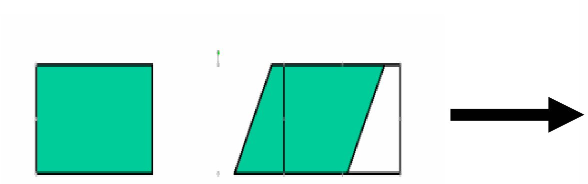


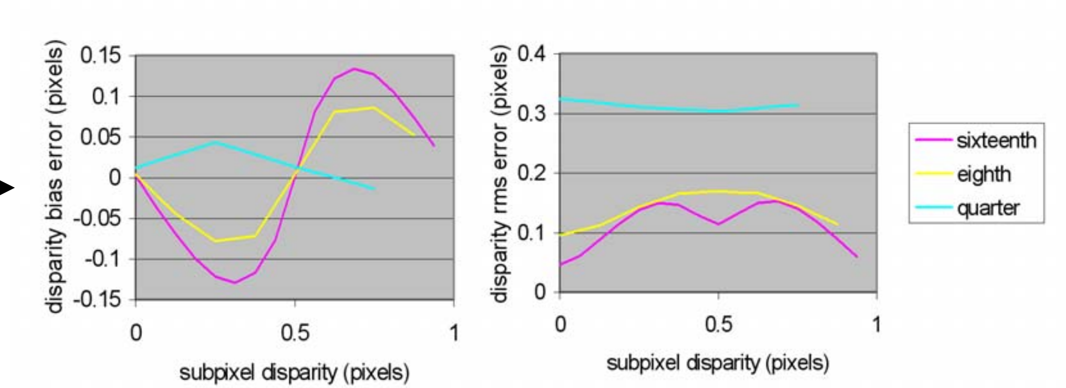


Error sources

- ***Limitations introduced by appearance change resulting from viewpoint change***
    - ***Keystoning and shear vary between cameras due to change in perspective viewpoint***







Introduce varying horiz. subpixel shift/image row

Intrinsic Range Error

- ***Subpixel disparity calculation has inherent limitation***
- ***Range has inverse dependence on disparity***
  - ***Downrange 3-D error has quadratic dependence on range***

$$\Delta Z = \frac{Z^2}{Bf} \Delta d$$

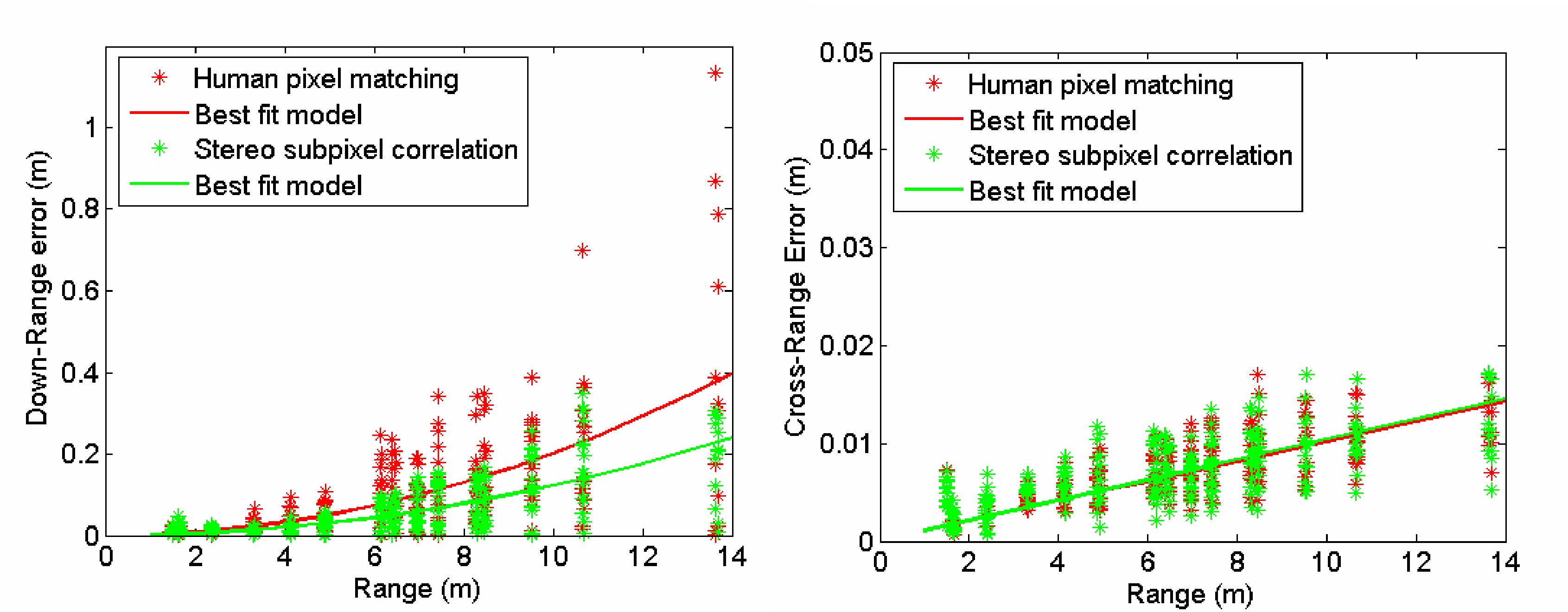
  - ***Crossrange 3-D error has linear dependence on range***

$$\Delta X = \frac{Z}{f} \Delta d$$

  - ***Δd assumed 1/3 pixel for MER***

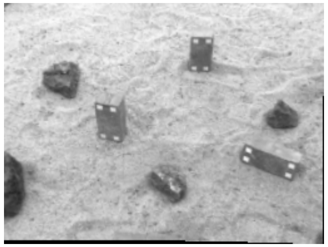
Intrinsic Range Error

Down and cross range errors. Ground truth from surveyed data.

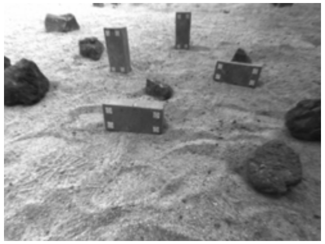


Sample application – camera handoff

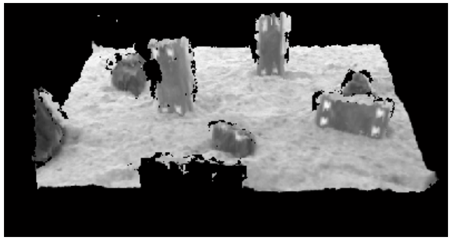
- *Camera handoff for target tracking*
  - *large viewpoint change (especially for Navcam -> Hazcam) complicates image based tracking*
  - *Range data has better invariance properties*
  - *First use camera and mast calibration to initialize handoff*
  - *Then use range from Hazcam stereo to project Navcam image onto Hazcam viewpoint*
  - *Correlate with reprojected template*



Navcam image

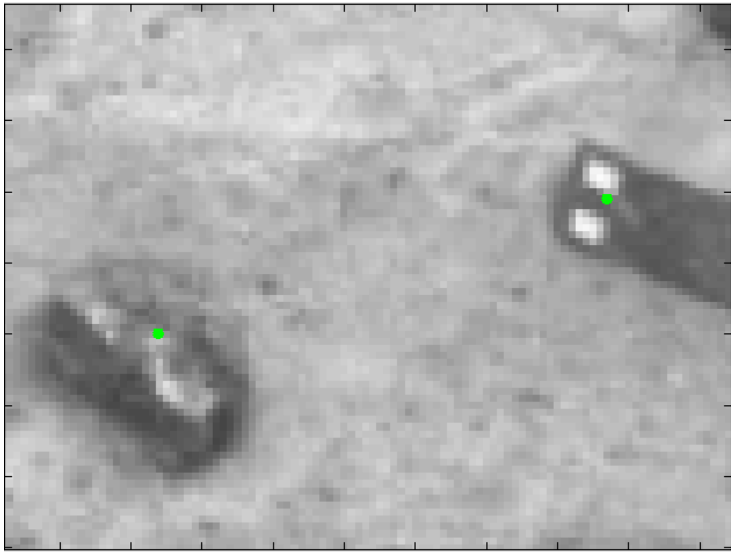


Hazcam image



Warped Navcam data from Hazcam viewoint

Sample application – camera handoff



Navcam

Hazcam

Geometric handoff from calibration in red. Stereo-based handoff in green.